



Fermi National Accelerator Laboratory

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**Electrical Design Note for a
5000 ADC, 230 μ H
Power Supply Filter Choke**

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1.0 INTRODUCTION

Most high current iron core filter chokes for DC power supplies at Fermilab are constructed from magnet laminations. Sometimes these laminations need to be trimmed to yield the correct gap. Occasionally magnets are used as DC chokes. Both of these approaches are expensive. The large forward drop across a magnet often is unacceptable and makes it very expensive to operate. For instance, operating a B2 magnet for one year at 3000 ADC costs about \$34,000. A properly designed choke could cut this operating cost to about \$4,000. It would also take less space and cause less floor loading, but its inductance would also be smaller. Constructing a customized choke from magnet laminations is still rather expensive from a labor and iron cost point of view, but at least the losses can be controlled by proper design. In general, these types of chokes are not required to be made precisely. The coil and iron dimensions are not very critical as long as they can handle the current and as long as the iron does not saturate. Therefore, it is very reasonable to make chokes from commercially available, standard, tape wound silicon steel transformer cores. Many manufacturers, such as Arnold Engineering, and others make a large variety of sizes in 12 mill thick or thinner laminations (Fig. 3). Completed cut cores cost about \$1.83/lb (1992).

Several cores can be put in parallel to yield the required amount of iron cross section, and the required gap can be made by inserting a standard thickness G-10 shim between the cut core halves. The gap prevents iron saturation. The coil, with the iron cores around it, can be mounted in a steel cradle which holds the assembly together.

This type of design has several advantages.

1. The choke design can be customized easily because of the large variety of sizes of commercially available cores.
2. The cost of steel cores is low compared to customized laminations, except probably for mass production. No custom punching dies need to be made.
3. The magnetic properties of the steel cores are superior and well published.
4. The frequency response is superior.
5. Assembly is fast. A 2500 lbs choke and completed coil can be assembled in about 2 manweeks after some practice.
6. Losses and voltage drops can be controlled by making the proper design choices.

This note describes the design of a 5000 ADC, 230 μH choke made from standard transformer cores. Five of these chokes have been made for CDF and MTF. NOTE: Special magnets can also be made using standard cores (Ref. 1).

2.0 CHOKE PARAMETER REQUIREMENTS

Both CDF and the Magnet Test Facility needed chokes to reduce the output voltage ripple of their 5000 A, 12 phase, unfiltered DC power supplies. Chokes rated about 200 μH at 5000 ADC, with a properly chosen capacitor, will cause sufficient ripple reduction. The voltage drop across the choke should not exceed 3 V, because of circuit voltage limits at the installation site. Thus the required choke has to be as follows:

- 2.1 $\sim 200 \mu\text{H}$ at 5000 ADC
- 2.2 $\leq 0.6 \times 10^{-3} \Omega$ at 60°C
- 2.3 Cooling water $\sim 1.5 \text{ GPM}$ at $\Delta P = 100 \text{ PSI}$

Comment:

The average coil operating temperature may be 60°C or less. The maximum inlet water temperature is 40°C maximum. The outlet cannot exceed 80°C , because the choke is protected against overtemperature (loss of cooling) with thermal switches (klixons) of 80°C . The coil insulation system is usually good for 140°C maximum, but a maximum operating temperature of 80°C is generally chosen in order to avoid cooling hose connection problems and possible steam formation at hotspots in the coil. The cooling water temperature will change according to a ratio of power versus flow rate as follows:

$$\Delta T \text{ } ^\circ\text{C} = \frac{3.8 \times \text{kW}}{\text{GPM}}$$

So, as a rule of thumb, we can say that with a practical cooling water temperature rise limit of 40°C , we need one GPM of cooling water flow for every 10 kW of coil losses.

3.0 CHOKE ELECTRICAL DESIGN

3.1 Steel Choice

For starters, choose a coil current density of 2000 A/inch^2 for the water cooled choke winding. This means that the steel cores have to have a winding space area of about:

$$\frac{5000}{2000} \times 1.25 \sim 3 \text{ inch}^2/\text{turn}$$

$$\frac{1}{1.25} = 0.8 \text{ is the estimated copper fill factor for the winding area}$$

The winding space must be able to accommodate several turns, because the inductance increases with the square of the turns. However, more turns also require the gap to increase, because otherwise the steel would saturate at full DC current. Increasing the gap reduces the choke inductance linearly. Choose $1\text{-}1/4" \times 1"$ copper with rounded corners and a $3/8"$ diameter cooling hole for the coil winding, because it is available as a leftover from the magnet factory. Each copper crosssection is 1.1 in^2 and yields $\frac{5000}{2.2} = 2,270 \text{ A/inch}^2$ for two conductors in parallel at 5000 ADC. We are now ready to select a core from a catalogue. Arnold core #AA554 has a winding space of $1\text{-}1/4" \times 2\text{-}1/2" \sim 28 \text{ inch}^2$ and can therefore accommodate 8 or 9 turns. The core has a steel crosssection of $2\text{-}11/16" \times 4"$, or $69.35 \times 10^{-4} \text{ m}^2$. This looks like a good choice. This core is easy to buy and weighs 98.5 lbs (or about 50 lbs / $1/2$ core) and is therefore easy to handle.

We are now getting ready to calculate the inductance per core with 8 turns, but we first have to make a choice for the maximum magnetic field strength in the steel so that it

does not saturate. Choose $B = 13 \text{ kGauss}$ (1.3 Wb/m^2) maximum from published BH curves. The ampereturns needed to drive the flux through the steel of the cores can be neglected. The steel ampereturns at 13 kG are a very small fraction of the ampereturns needed to drive the same field through the choke gap. With these choices it is possible to calculate the gap and the inductance per core as follows:

$$\begin{aligned} B &\sim 1.3 \text{ Wb/m}^2 \\ N &= 8 \\ I &= 5000 \text{ A} \\ G &= ? \end{aligned}$$

How large a gap G is needed so that the core does not saturate? The cut core needs two gaps in series, one on each side. The gap can be calculated from:

$$\begin{aligned} B &= \mu_0 H & \mu_0 &= 4\pi \times 10^{-7} \text{ (mks system)} \\ & & H &= \text{AT/m} \end{aligned}$$

$$B = \frac{4\pi \times 10^{-7} \times 8 \times 5000}{2G} \sim 1.3$$

This yields $G = 1.93 \text{ cm}$. Select $G = 3/4"$ thick G10.

$$\text{Then: } B = \frac{4\pi \times 10^{-7} \times 8 \times 5000}{2 \times 0.75 \times 2.54 \times 10^{-2}}$$

$$B = 1.319 \text{ Wb/m}^2$$

The flux ϕ per core is the crosssectional area times the field strength.

$$\phi/\text{core} = 1.319 \times 69.35 \times 10^{-4}$$

$$\phi/\text{core} = 91.5 \times 10^{-4} \text{ Wb}$$

The inductance per core is the coupled flux per Ampere.

$$\text{Thus: } L/\text{core} = \frac{N\phi}{I}$$

$$L/\text{core} = \frac{8 \times 91.5 \times 10^{-4}}{5000}$$

$$L/\text{core} = 14.64 \times 10^{-6} \text{ H}$$

With 16 cores the inductance is:

$$L/16 \text{ cores} = 234 \times 10^{-6} \text{ H}$$

This looks reasonable and the coil can now be calculated. The steel cores can be arranged in two rows of eight cores. This is similar to the shell type, double core, single coil configuration shown in Fig. 3.

3.2 Coil Design

A preliminary design of the choke is shown in Drwg. #ATV090892CDF. The coil carries 5000 A, has 8 turns and uses two 1" x 1-1/4" copper conductors in parallel. Each conductor has a 3/8" diameter cooling waterhole and a copper crosssection of 1.1 inch². The current density in the copper is 2273 A/inch² at 5000A. Assume an average coil operating temperature of 60°C, which is about the worst case from a voltage drop point of view.

Properties of copper are mostly listed at 20°C and per cm³ or inch³, but it is handier to list them at operating temperature and sizes as below:

Typical Cu resistance at 60°C: $R_{60^{\circ}\text{C}} = 9.6771 \times 10^{-6} \Omega/\text{in}^2/\text{ft}$

Typical Cu weight: $W = 3.86 \text{ lbs/in}^2/\text{ft}$

Resistance temperature
coefficient per °C at 20°C: $\alpha = 0.00393$

With this information it is easy to calculate the coil.

$$I = 5000\text{A}$$

$$N = 8$$

Total Cu crosssection	= 2.2 inch ²
Coil average turn length	= 90"
Total coil weight	~ 516 lbs (120' of Cu)
Coil resistance at 60°C, $R_{60^{\circ}\text{C}}$	= $0.38 \times 10^{-3} \Omega$
Coil voltage drop at 5000A, 60°C	= 1.9 V
Coil losses at 5000A, 60°C	= 9.5 kW
Estimated flow at $\Delta P = 100 \text{ PSI}$	~ 10 GPM
Minimum needed flow at 40°C water temperature rise, or 20°C average coil temperature rise	= 1 GPM

This coil will work. The coil is wound on a winding fixture, after which B stage tape is applied around the two copper conductors in parallel. After that the coil receives a ground wrap and is cured on the winding fixture. For reference see drawings 5525-ME-274925 through -274929. There was some keystoneing at the coil bends that needed to be

removed. The leads of the coil are made long for ease of connection at the installation site. Copper flags are brazed to the leads for power connections.

4.0 CHOKE ASSEMBLY

The choke is assembled in a shop and requires the use of a small crane. Two rows of eight cores are banded around the coil, with two G-10 shims used as spacers to create the gap. The winding surface walls of the cores are lined with a medium-hard rubber material and the cores are shimmed for a snug fit around the coil before banding (Fig. 3). The cores are separated by a thin piece of DMD (or other insulation material) to prevent possible iron shorts across the lamination of adjacent cores. After this, the cores are put in a cradle (Drwg. ATV010892CDF, Sh 5). A similar cradle is put on the top and both cradles are thereafter welded together with side plates. The banding buckles fall in the cavity under the side plates between the top and bottom caps. Stops are installed to prevent the assembly and the coil from sliding inside. The cores are not all equal in size and there are cavities under some cores as they sit in the "box". One gallon of epoxy is therefore poured in the bottom cradle. After the bottom epoxy is cured, the choke is turned over and another gallon of epoxy is poured in at the previous top cradle. This secures the cores and completes the assembly of the chokes. The assembly of the chokes was done at MAB. The coils were made at the Magnet Factory.

5.0 DRAWINGS

The following is a list of drawings for the choke:

#ATV010892CDF, SH1	- Power supply choke for CDF 5000ADC, 230 μ H, 0.4 Ω
#ATV010892CDF, SH2	- same as above
#ATV010892CDF, SH5	- Power supply choke for CDF core cradle
#ATV010892CDF, SH6	- Power supply choke for CDF spacer and nameplate
5525-ME-274925	- Conventional magnet facility choke coil - coil assembly
5525-ME-274926	- Conventional magnet facility choke coil - coil crosssection
5525-ME-274527	- Conventional magnet facility choke coil - shims
5525-ME-274528	- Conventional magnet facility choke coil - winding fixture
5525-ME-274929	- Conventional magnet facility choke coil - curing fixture

6.0 TESTING

The following were tested:

- | | | |
|----|-----------------------------------|---|
| 1) | Cooling flow | - 3.8 GPM at $\Delta P \sim 75$ PSI |
| 2) | Pressure test | - 375 PSI for 15 min |
| 3) | Hi-potential test 2500 Vdc, 1 min | - > 2500 M Ω |
| 4) | DC resistance | - $0.23 \times 10^{-3} \Omega$ at $\sim 20^\circ\text{C}$ |
| 5) | Inductance | - > 230 μH ⁽¹⁾ |

(1) The results of the inductance test were not meaningful. The measured values at low operating current were on the order of 460 mH. This is probably caused by flux bypassing the gap via the banding buckles and the steel cradle spacer. These parts will saturate at higher currents, but testing at high current was not practical in the assembly area.

7.0 COST

The cost of the winding/curing fixture was \$4300.00 excluding design cost.

Material cost per choke:

16 Cores	-	\$2940.00	
2 cradles, 2 side plates, miscellaneous	-	\$ 175.00	
516 lbs copper (free from stock)	-	\$1500.00	(estimated value)
Total material	~	\$5000.00	

The labor cost for winding and curing of the coil is not precisely known, but is about \$7,500.00. Choke assembly takes about 2 manweeks.

8.0 COMMENTS

The design of this choke or similar chokes is easily modified by changing the gap, the number of turns, or the number of cores. For instance, we could put all windings in series and end up with 16 turns at 2500A. This would yield a 0.92 milliHenry choke at 2500 ADC.

Another interesting idea is to vary the thickness of the G-10 shims installed in different cores. A smaller gap causes the inductance per core to increase, but also causes it to saturate at a

lower d.c. current value. For instance, cutting the gap in half causes the inductance to increase by a factor of two, but also causes saturation at half of the original gap saturation current..

Saturation causes the inductance to decrease to a low value. We can imagine a simplified saturation effect and say that the inductance becomes zero after saturation and that the steel abruptly saturates. Each core of the 5000 A choke would then contribute $14.6 \times 10^{-6} \text{H}$ to the total choke below the saturation current and none above saturation, as shown in Fig. 1.

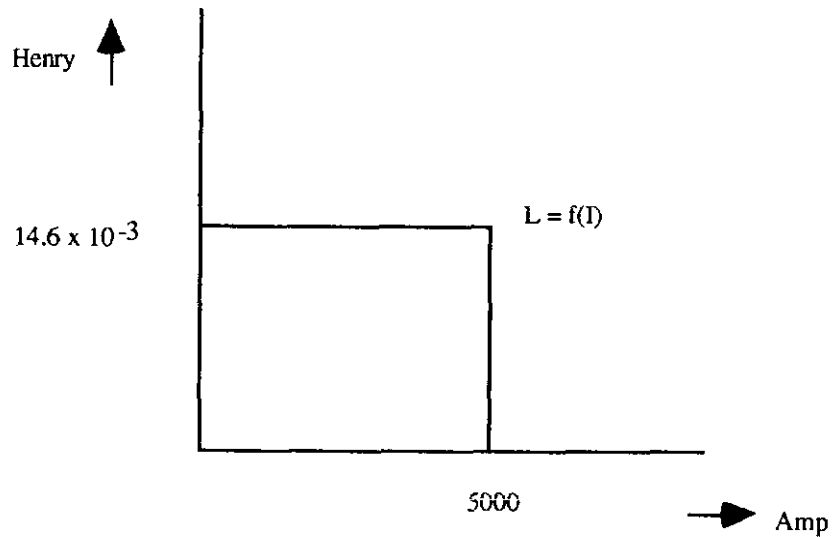


Figure 1: Simplified inductance per core.

Now imagine that we use different gaps in the 16 cores as follows:

	Gap	Core Saturating Current Amp	Contribution to Inductance Below Saturation μH
4 Cores	$2 \times 3/4$	5000	58.4
4 Cores	$0.8 \times 2 \times 3/4$	4000	83.0
4 Cores	$0.6 \times 2 \times 3/4$	3000	97.0
4 Cores	$0.4 \times 2 \times 3/4$	2000	146.0

This yields a total choke inductance of:

Operating Current AMP	Total Choke Inductance μH
5000	58
4000	141
3000	238
2000	384

The inductance of this tapered gap choke as a function of the current is plotted in Figure 2.

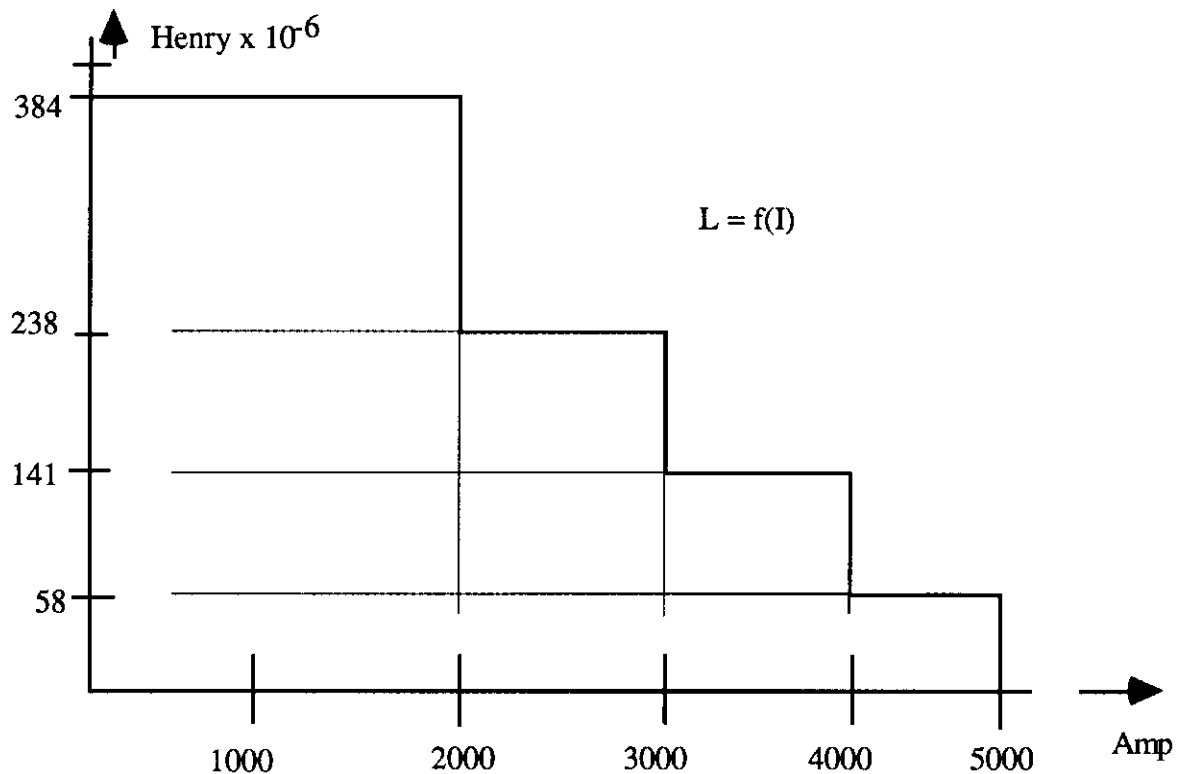


Figure 2: Tapered gap choke

Other combinations can be made. This is interesting, because power supply ripples are about twice as large (12 phase unfiltered) at medium output voltage than at full output. The ripple filter choke inductance can therefore be smaller at high power supply output. Lighter weight tapered gap chokes could therefore be just as effective, when used as power supply ripple filter chokes.

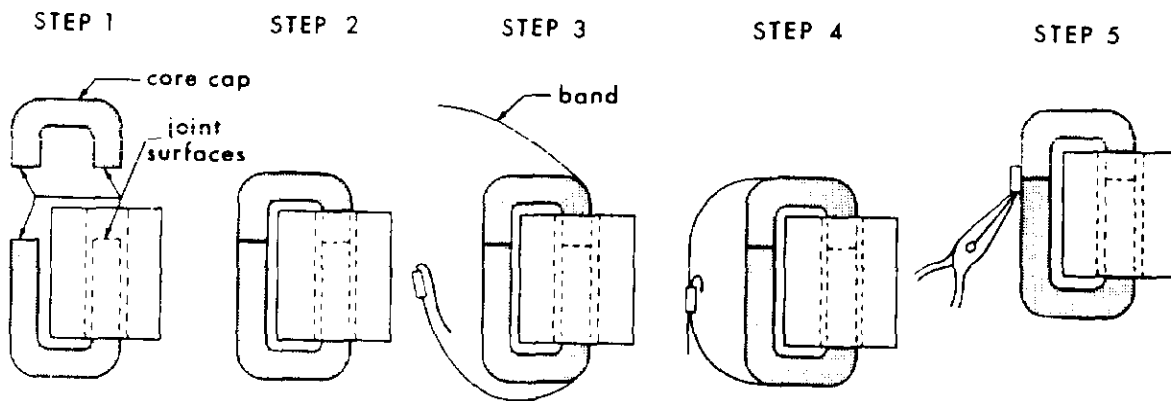
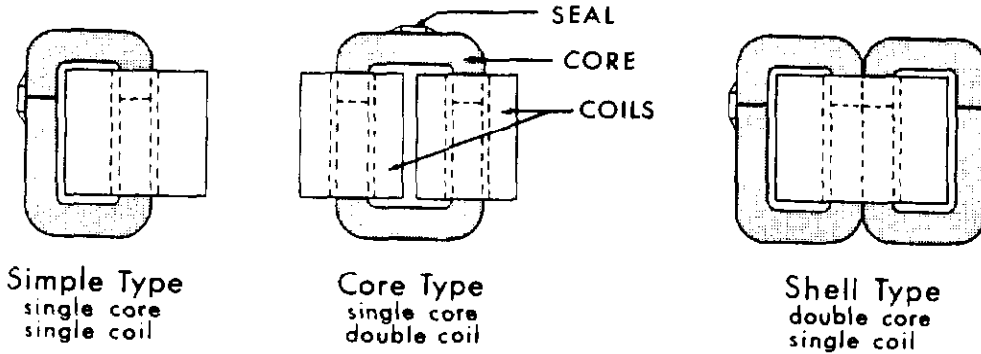
9.0 ACKNOWLEDGEMENT

The assembly of the chokes was coordinated by John Juneau at MAB. He did an excellent job.

10.0 REFERENCES


- (1) TM1605, A.T. Visser, July 1989, A novel flattop current regulated energy discharge type pulsed power supply and magnet yielding 4.4 kGaussmeter for 6 milliseconds.

BANDING DATA



Core Strip Width (in.)	Core Cross-Section (D × E) - in ²	Band Size (in.)	No. Bands Required	Seal Dimension (in.)	Banding Force (lb.)
Any	.188 or less	3/16 x .006	1	3/16 x 1/4	37.5
3/8 or larger	.188 to .375	3/8 x .006	1	3/8 x 3/8	75
3/8 to 1-1/2	.375 to .75	3/8 x .012	1	3/8 x 3/8	150
1-5/8 or larger		3/8 x .006	2	3/8 x 3/8	75
1/2 to 1-1/8	.75 to 1.5	3/8 x .012	1	3/8 x 3/8	150
1-1/4 or larger		3/8 x .012	2	3/8 x 3/8	150
3/4 or larger	1.5 to 3.0	3/4 x .023	1	7/8 x 1-7/8	600
3/4 or larger	3.0 to 4.25	3/4 x .035	1	7/8 x 1-7/8	900
2 or larger	4.25 to 6.0	3/4 x .023	2	7/8 x 1-7/8	600
3-1/4 or larger	6.0 to 9.0	3/4 x .023	3	7/8 x 1-7/8	600
3-1/4 or larger	9.0 to 13.5	3/4 x .035	3	7/8 x 1-7/8	900

Figure 3

	ENGINEERING NOTE	SECTION	PROJECT	SERIAL CATEGORY	PAGE					
SUBJECT	POWER SUPPLY (CHOKE FOR CDF)	EEO	CDF	NAME A.T.VINNER	1					
5000ADC, 230 VAC, 2.4 A										
DATE 1/8/92 PREL.										

DRWD ATV010892 CDF
1H1
REF 9204 ED 173037

CHOKE

$$B = \frac{1}{4} H, N = 8, I = 5000 A$$

$$B = \frac{4\pi \times 10^{-7} \times 8 \times 5000}{2 \times 0.75 \times 2.54 \times 10^{-2}} = 1.319 \text{ Wb/m}^2$$

$$\Phi = 8.2 \text{ (NEGLECT IRON AT)}$$

$$\Phi / \text{CORE} = 1.319 \times 64.35 \times 10^{-4} = 91.49 \times 10^{-4} \text{ Wb}$$

$$L / \text{CORE} = \frac{N^2}{I} = \frac{8 \times 91.49 \times 10^{-4}}{5000}$$

$$L / \text{CORE} = 14.64 \times 10^{-6} H$$

$$L / 16 \text{ CORES} = 234.2 \times 10^{-6} H \text{ (UP TO 5000 ADC)}$$

COIL AVERAGE TURN LENGTH 90"

$$CU \text{ CROSS} = 1.1 \text{ Wb}^2, 4.3 \text{ LBS/FT}$$

$$CU R_{200} = 8 \times 10^{-6} \Omega / \text{FT}$$

$$R_{\text{COIL } 200} = \frac{1.8 \times 90}{112} \times 8 \times 10^{-6} = 0.24 \times 10^{-3} \Omega$$

$$R_{\text{COIL } 600} = 0.24 \times 10^{-3} \times 110 \times 0.00393 = 0.038 \text{ m}^3 \Omega$$

$$V_{\text{COIL AT } 5000A} = 1.9 V$$

$$\text{COIL LOSSES} = 9.43 \text{ KW AT } 5000A \text{ 600}$$

$$\text{NEEDED COOLING} \sim 1 \text{ GPM AT } 27 \sim 38^\circ C$$

$$CU \text{ LENGTH/WINDING} \sim 60 \text{ FT, } 258 \text{ LBS}$$

$$\text{FLOW/WINDING} \sim 5 \text{ GPM AT } 27 \sim 100 PSI$$

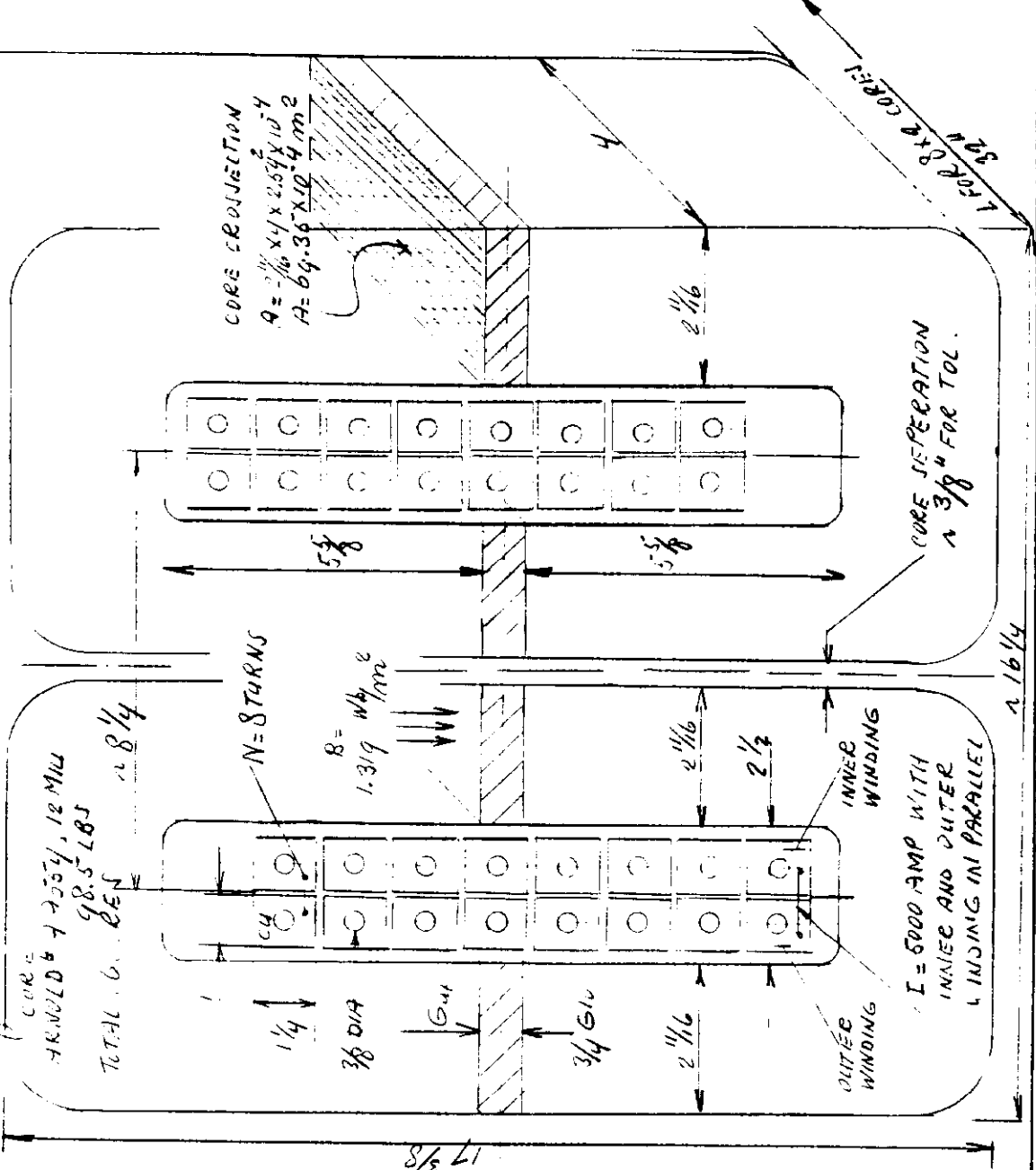
$$\text{TOTAL COIL WEIGHT} \sim 516 \text{ LBS (4 W/RAFT)}$$

$$\text{FLOW} \sim 10 \text{ GPM AT } 27 \sim 100 PSI \text{ (PARALLEL WATER)}$$

$$\text{W/RAFT - } 80^\circ C \text{ AT } 100 PSI$$

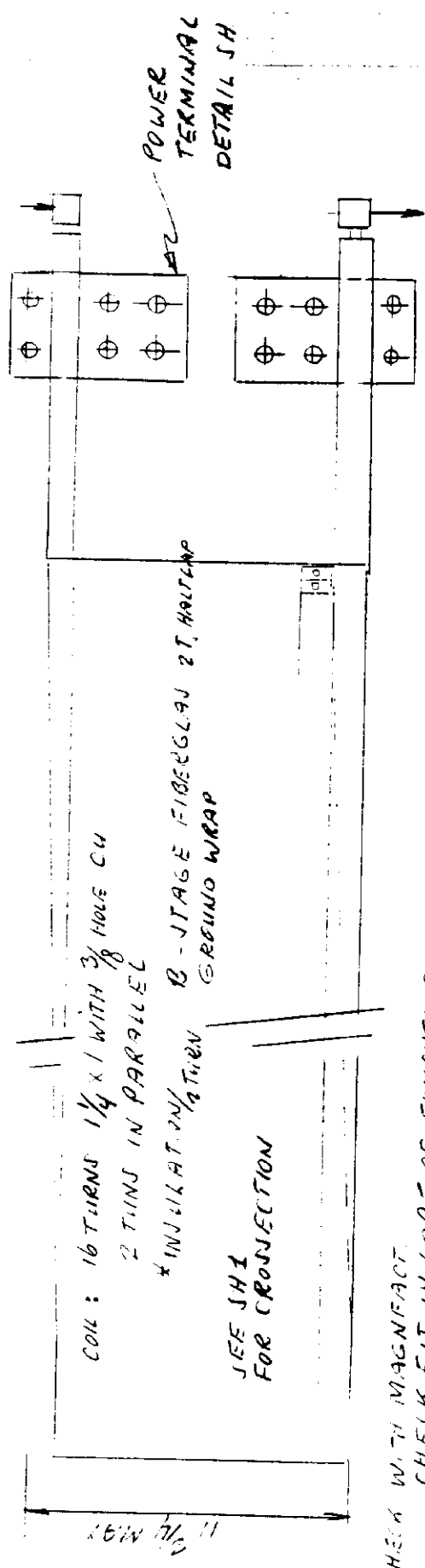
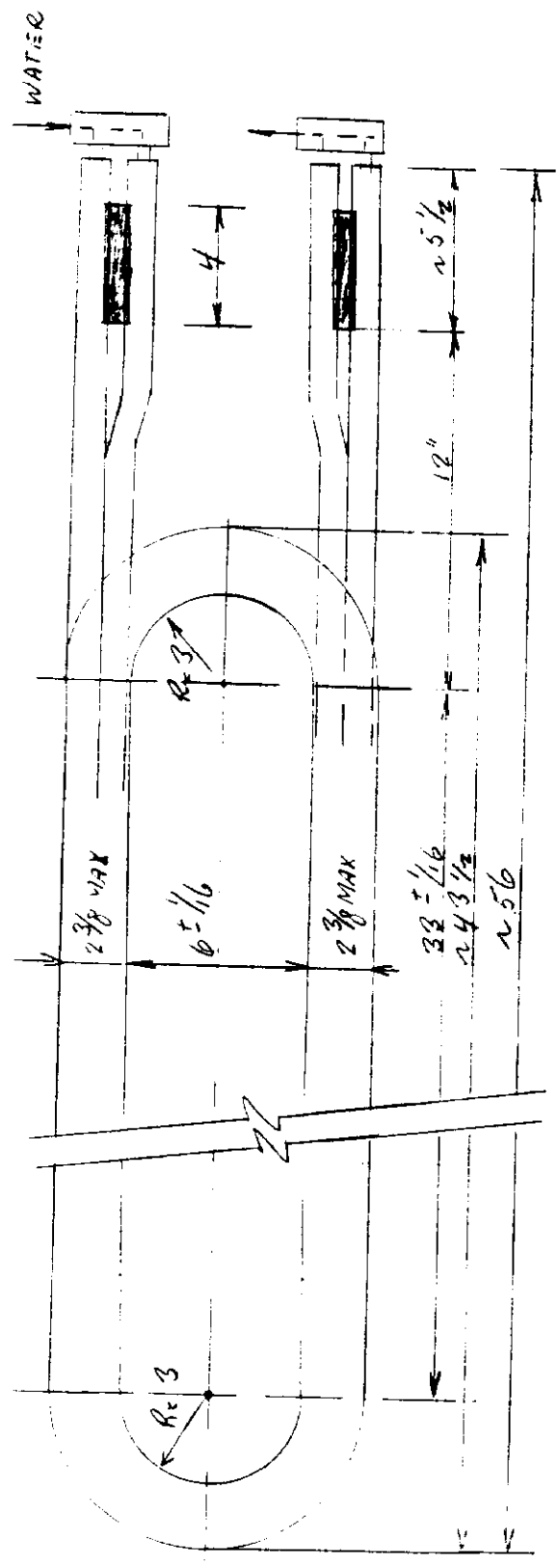
$$\text{TOTAL STL WEIGHT} \sim 1576 \text{ LBS}$$

$$\text{TOTAL INDUCTOR WEIGHT} \sim 2500 \text{ LBS}$$




ENGINEERING NOTE POWER SUPPLY CHOME FOR COF COIL	SECTION	PROJECT	SERIAL CATEGORY	PAGE
	FED	COF	KEPHART	2
	NAME A.T. Visser			
DATE		REVISION DATE		
1/18/92				

DRW# ATV00042 CDF
(PREL) SH 2

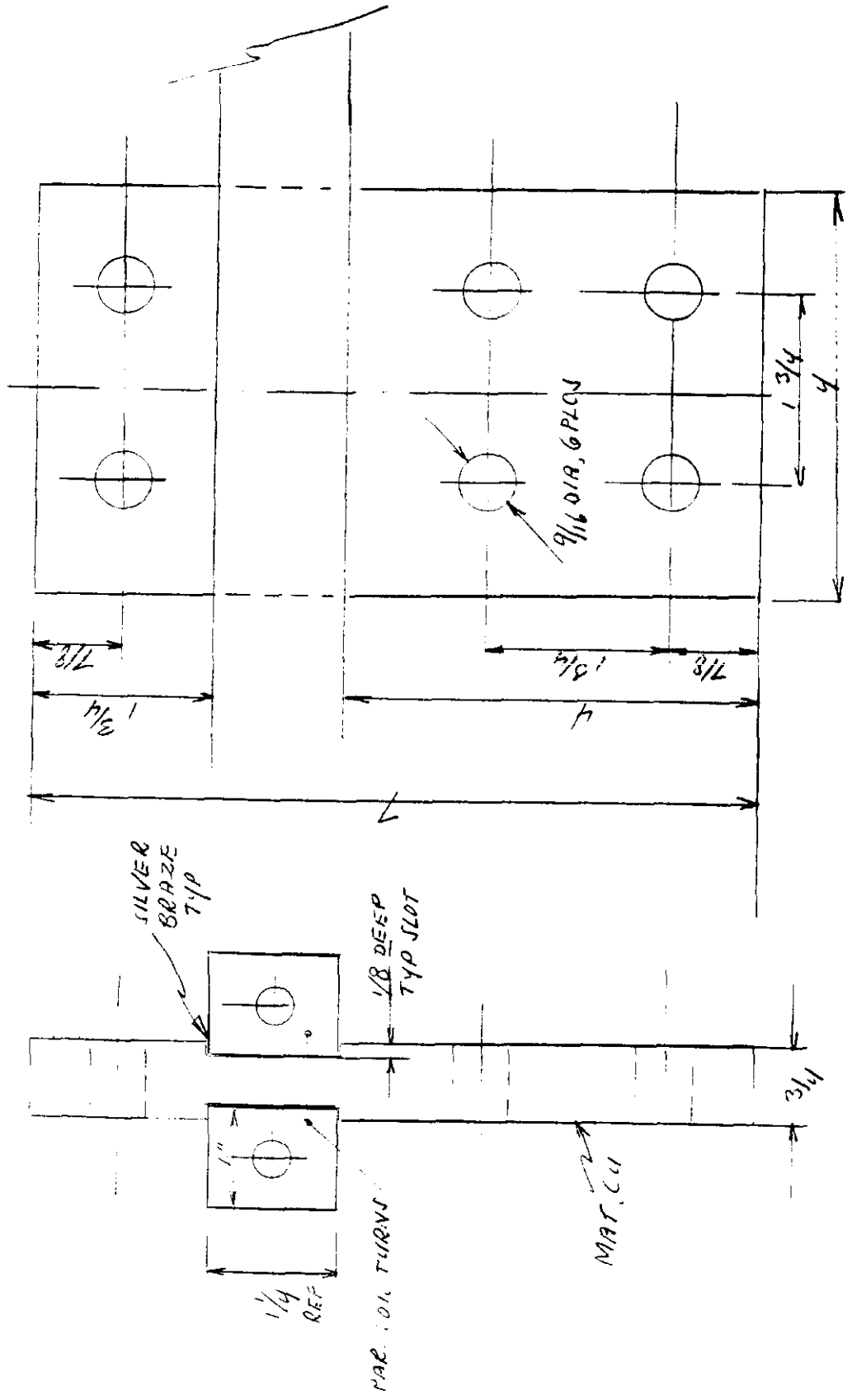


*CHECK WITH MAGNET
CHECK FIT IN CORE OF FINISHED COIL


REF 9204ED 173051

 ENGINEERING NOTE	SECTION	PROJECT	SERIAL CATEGORY	PAGE
	EED	CDF	KEPHART	4
SUBJECT POWER SUPPLY CHANGE FOR CDF HOME POWER TERMINAL	NAME	DATE	REVISION DATE	
	AT VINNER	1/12/92		

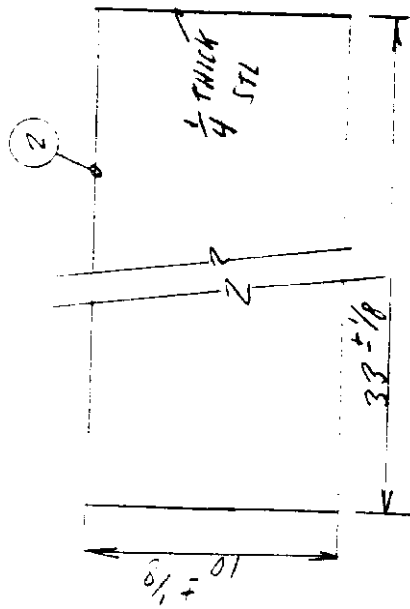
DRW# ATV 010892 CDF
JH4



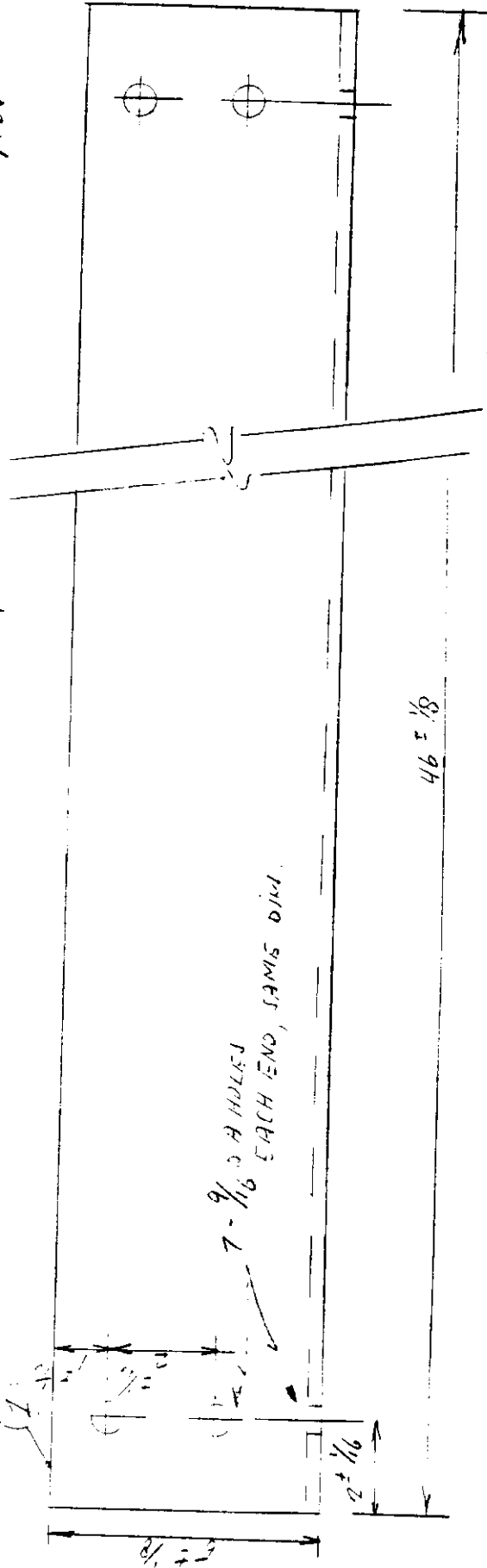
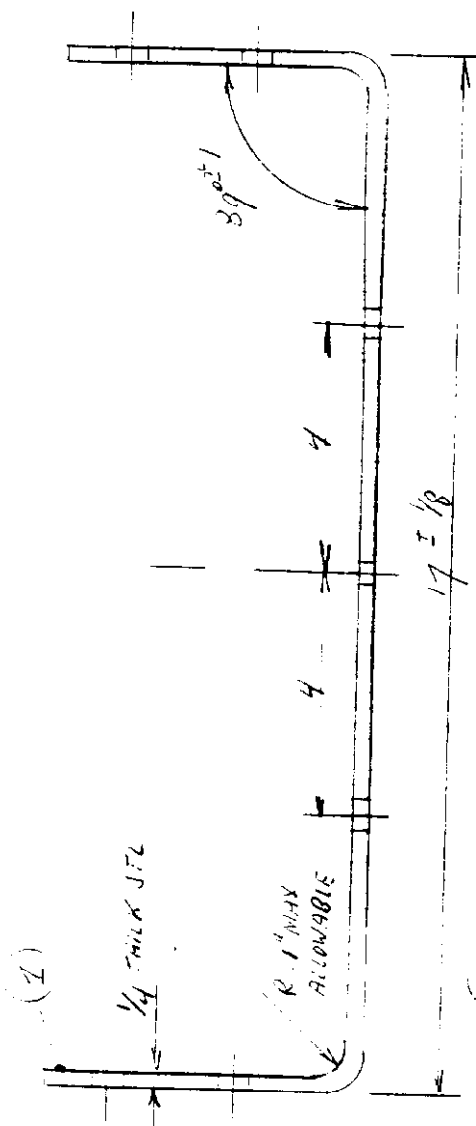
REF 4204 ED 173051

 ENGINEERING NOTE	SECTION	PROJECT	SERIAL CATEGORY	PAGE
	EE0	CDF	HEPHART	5
SUBJECT		NAME		
POWER SUPPLY CHOKES FOR CDF		A.F. VIJVER		
CORE COUPOLE		DATE	REVISION DATE	
		1/8/92		

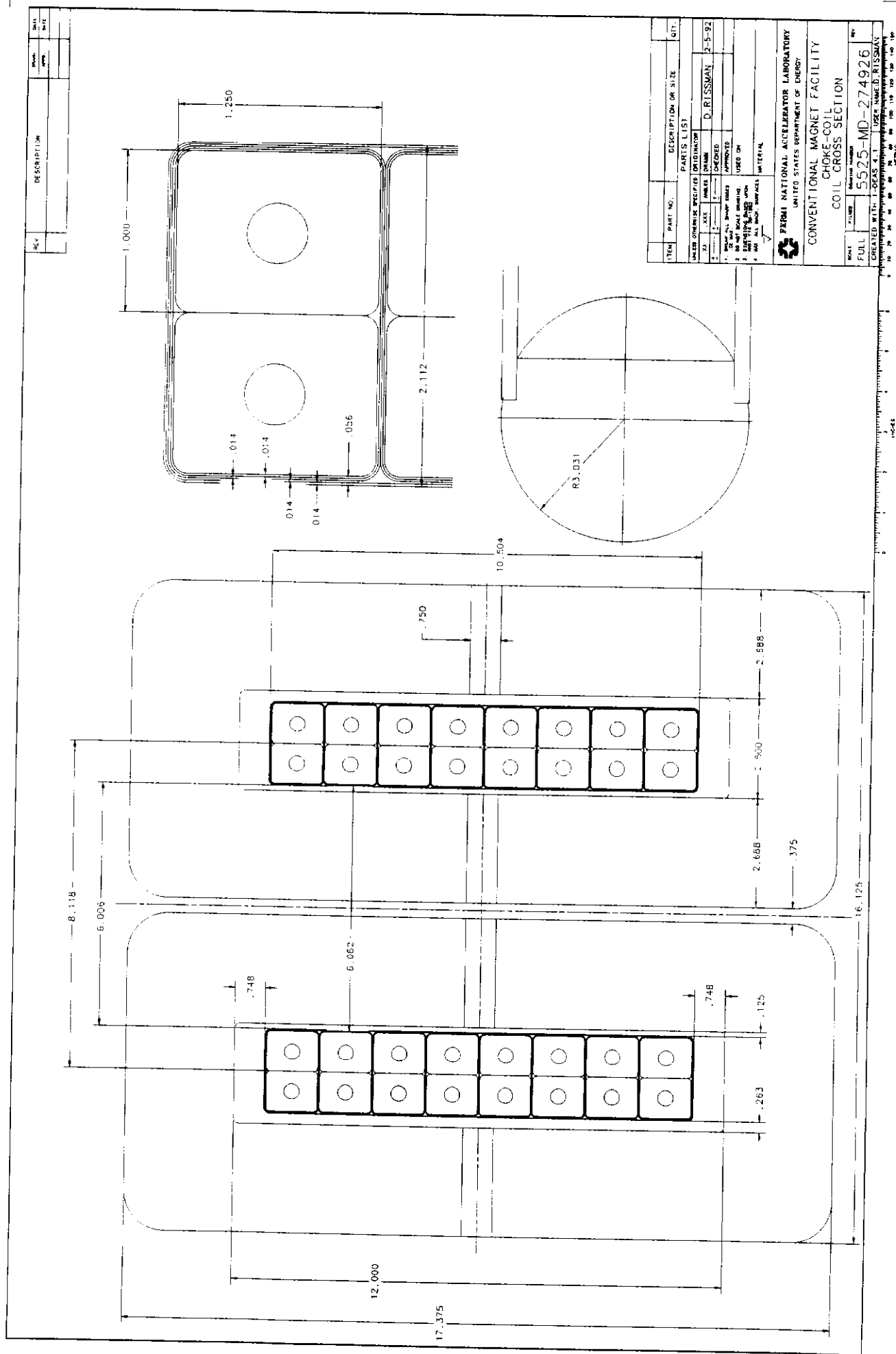
DRW 4, ATVOIDS QCDF
JH5-



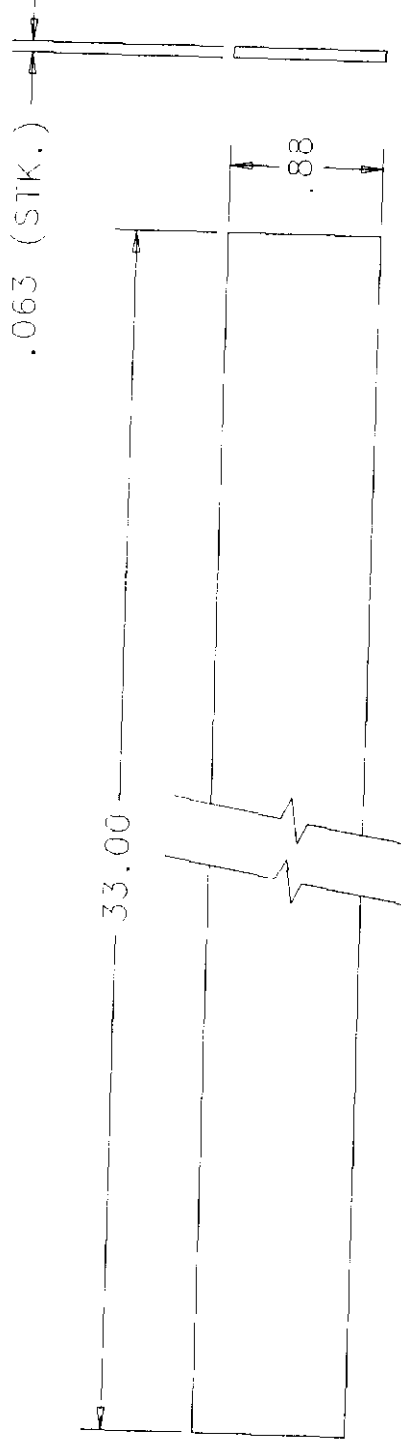
ITEM 1 - 4 PCS
2 - 4 PCS




REMOVE BURR, SCALE, RUST
REF Q204 ED173051

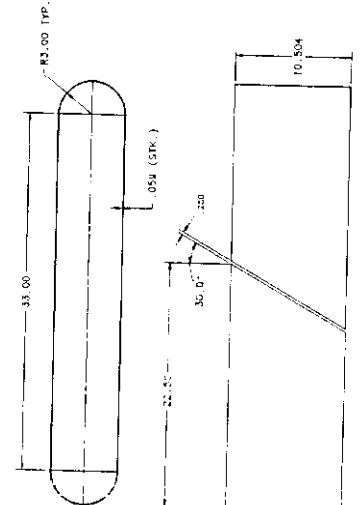
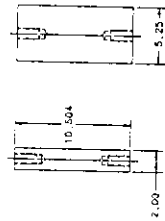
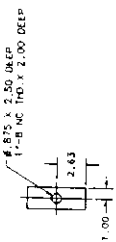
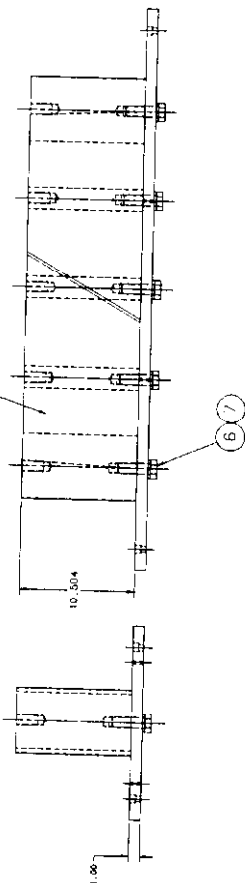
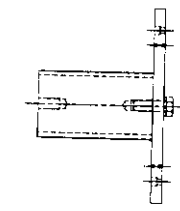
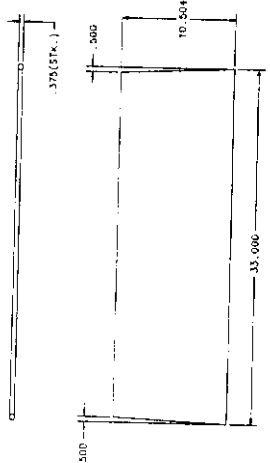
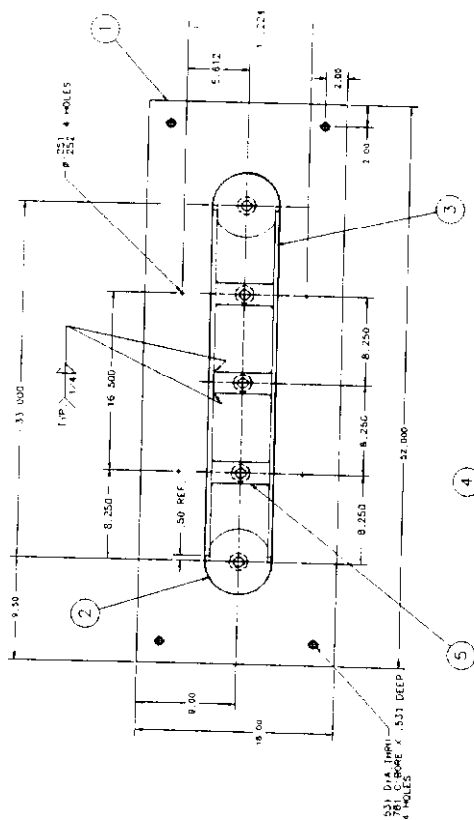
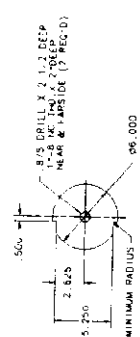


REV.	DESCRIPTION	DRAWN	DATE
		APPD.	DATE



ITEM	PART NO.	DESCRIPTION OR SIZE	QTY.
PARTS LIST			
UNLESS OTHERWISE SPECIFIED		ORIGINATOR	
XX	XXX	ANGLES	DRAWN
1.03			2-27-92
		CHECKED	
		APPROVED	
1. BREAK ALL SHARP EDGES .02 MAX		USED ON ME-274928	
2. DO NOT SCALE DRAWING.			
3. DIMENSIONS BASED UPON ANSI Y14.5M-1982			
4. MAX. ALL MACH. SURFACES			
1257		MATERIAL ALUM. 6061-T6	
 FERMI NATIONAL ACCELERATOR LABORATORY UNITED STATES DEPARTMENT OF ENERGY			
CONVENTIONAL MAGNET FACILITY CHOKE-COIL SHIMS			
SCALE	FULL	DRAWING NUMBER	REV.
		5525-MA-274927	
CREATED WITH I-DEAS 4.1		USER NAME: D. RISSMAN	

NO.	DESCRIPTION	DATE	BY
1	AS-BUILT RELEASE	10-24-71	W. J. B.



7	8/32 DRILL X 2 1/2 DEEP	1
8	1/8 MC THO X 2 DEEP	1
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100	1/8 MC THO X 2 DEEP	1

CONVENTIONAL MAGNET FACILITY
CHOKE-COILS
WINDING FIXTURE

